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Uncovering energy saving and carbon reduction potential from recycling wastes: A case of Shanghai in China

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ABSTRACT

With fast development and urbanization, Chinese cities are facing several challenges including issues of environmental pollution, climate change, resource depletion and landfills shortage. Waste recycling is one effective way to respond these challenges. Under such a situation, this paper aims to evaluate energy saving and carbon reduction potential of recycling wastes by taking Shanghai, the biggest city in China, as a case study. Results show that 8.7 Mt standard coal (tce) and 16.81 Mt CO_2 could be reduced under current recycling system in Shanghai. And recycling of waste steel and nonferrous metals were the two dominant contributors, accounting for about 44% and 42% of energy saving, and 60% and 33% of CO_2 reduction, respectively. If the recycling rates of main recyclable wastes were improved to 100%, additional 6.44 Mt energy and 10.02 Mt CO_2 could be further saved, mainly from recycling waste glass, waste plastic and waste metals. Adoption of RPF (Refuse Plastic & paper Fuel) could further contribute to 1.24 Mt energy saving and 2.67 Mt CO_2 reduction. Finally, policy implications on establishing a mature recycling system and promoting RPF technologies are discussed, in which the potential on reducing total energy consumption and CO_2 emission of Shanghai can reach 6.6% and 4.9%, respectively.

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1. Introduction

"Besieged by wastes" is becoming a severe challenge for many cities due to increasing quantity of municipal solid waste (MSW), particularly in those fast developing countries because of their rapid population increase, industrialization and urbanization (Fidelis and Colmenero, 2018; Tan et al., 2015). As the largest MSW production country in the world since 2004 (Havukainen et al., 2017; Mian et al., 2017), China is now facing serious challenges on managing MSW managements. Two-thirds of Chinese cities are lack of landfill sites (Zhao et al., 2016). Another issue is the inefficient urban recycling system in China. Landfill and incineration are the dominant waste treatment methods in China, with shares of about 58% and 36% in 2016, respectively (National Statistics Bureau of PRC, 2017). While the overall wastes recycling rate is very low, probably less than 2% (Zhang et al., 2016), which is much lower than developed countries, such as 62% for Germany and 59% for Singapore (Fig. 1) (Mian et al., 2017).

Therefore, it is urgent for China to promote urban waste recycling. Ministry of Commerce (MOFCOM) and National Development and Reform Commission (NDRC) of China have released several policies to promote the establishment of urban waste recycling system, such as the urban waste recycling pilot program (MOC, 2006, 2009, 2012). Ambitious targets were also set in China's 13th *Five-year-plan on Construction of National MSW Treatment Facilities*, in which the recycling rate was set as 35% for MSW and a mature recyclable wastes recycling system should be established in 2020 (NDRC and MoHURD, 2016). Many researchers have made qualitative studies on how to mature China's urban recycling system and improve recycling rate. For example, they identify the recycling barriers as outdated development concepts and disordered marketing rules (Ouyang and Cao, 2012), propose to increase the accessibility of recycling facilities and avoid behavior barrier (Zhang et al., 2016), advocate the establishment of formal recycling market and information platform (Xiao et al., 2018), propose to increase source separation rate and public awareness & incentives (Zhuang et al., 2008). However, the recycling potential and

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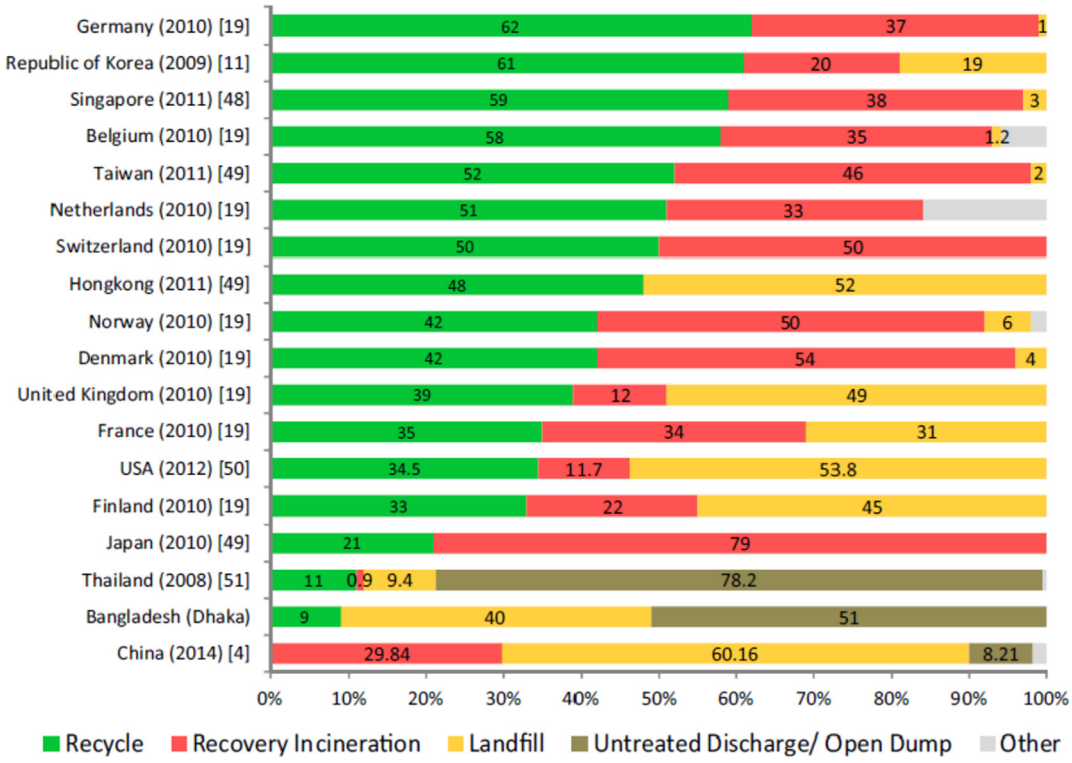

Fig. 1. MSW treatment situation of different countries (Mian et al., 2017).

corresponding environmental benefits of recycling MSW are still unknown and need to be quantified so that more concrete evidence can be provided to those decision makers.

Many of existing studies have been conducted to investigate the economic and environmental effect of MSW treatment technologies but few on waste recycling. For instance, the environmental benefit of waste to energy (WtE) technology related to landfill treatment, landfill gas recovery and incineration treatment. In this regard, Mboowa et al. (2017) evaluated the component of landfill gas in Dhanbad and confirmed that it could be equal to about 31.3% of the energy of bituminous coal. Tan et al. (2015) compared the energy, economic and environmental impact of different WtE technologies in Malaysia. Assamoi and Lawryshyn (2012) evaluated the environmental performance and discounted costs of the incineration and landfilling of MSW from a life cycle perspective. Zhao et al. (2016) conducted an economic benefit analysis of one WtE plant in China and identified that feed-in tariff and tipping fee were the main factors for its stable operation. Secondly, studies on the mechanical and biological treatment (MBT) technologies, such as composting and fermentation, and refuse-derived fuel (RDF) that uses highly combustible residual waste such as plastics and some biodegradable materials as fuel for cement kilns, have also been conducted (Sapuay, 2016). In this regard, Ripa et al. (2017) conducted an LCA analysis to investigate environmental costs and benefits of MBT technology that boosted separation of biomass for energy generation in combined heat & power plant and other recoverable fractions (metals, plastic). Study by Panepinto et al. (2015) shows that MBT was preferable from the environmental point of view, while the pyro-gasification option was better from the economic point of view. In addition, RDF is an emerging and promising clean technology and received more attentions. In this regard, Havukainen et al. (2017) investigated the environmental impact of RDF production and incineration to substitute the co-incineration of MSW with coal in Hangzhou using LCA program and found that the potential can be up to 33% greenhouse gas emission reduction, 90% acidification reduction and 1200% eutrophication reduction. Finally, the establishment of an integrated MSW management system that includes source separation, MBT, landfill and incineration receives more attention in order to identify and optimize the environmental benefit of MSW management. For example, Parkes et al. (2015) conducted a LCA analysis on ten integrated waste management systems for three potential post-event site design scenarios in the London Olympic Park. Chi et al. (2015) compared four integrated MSW management systems using LCA method and found that a total 30%, 18%, 28% and 29% of global warming, acidification, nutrient enrichment and photochemical ozone formation could be saved, respectively. Sun et al. (2018) designed different urban symbiosis systems and evaluated their energy recovery and carbon emission reduction effect. However, only a few studies on energy saving and CO_2 reduction benefit of recycling wastes have been performed due to a lack of sufficient data and appropriate evaluation methods (Chester et al., 2008). Simonetto et al. (2013) and Lino et al. (2010) assessed the energy savings in waste recycling for two Brazil cities. Ayodele et al. (2018) quantified the energy saving effect of recyclable waste recycling for Nigeria to be about 89.99 toe (1046.43 GW h) per year.

Under such a circumstance, this study aims to quantify energy saving and carbon emission reduction benefit of recycling wastes in China using embodied energy & CO_2 method from a life cycle perspective. Particularly, Refuse Plastic & paper Fuel (RPF), an updated solid fuel of RDF, will be introduced and its life cycle energy saving and CO_2 reduction effect will be evaluated. Shanghai, one of the first batch waste recycling pilot cities in China, will be selected as a case study. The remainder of the paper is organized as follows. Section 2 introduces the background and recycling information of the case city, Shanghai. Section 3 explains the methods used to evaluate energy saving and carbon emission reduction, as well as data sources. Section 4 presents research results. Section 5

discusses policy implications. Finally, section 6 draws research conclusions.

2. Waste recycling in Shanghai

Shanghai, the biggest and most developed city in China, is working hard to present a leading model on managing its solid wastes by encouraging recycling activities. It was selected as one of the first batch of pilot recycling cities by the national government. Shanghai locates in the eastern coastal part of China (30° 40′–31° 53′ N, 120° 51′–122° 12′ E) and has an area of about 6340 km^2. The total population of Shanghai was approximately 24.15 million people in 2016 and its total gross domestic value (GDP) reached 2.8 trillion RMB in 2016 (National Bureau of Statistics of China, 2017). Shanghai becomes the largest city in terms of MSW production, about 8.8 Mt in 2016 (MEP, 2017). Over half of its MSW (52.5%) was landfilled and only 2.5% was recycled (Lu, 2012). Therefore, it is crucial for the Shanghai government to reduce the total quantity of MSW through source separation & recycling.

In 2010, Shanghai was listed as one of the first batch pilot recycling cities by the national government to improve its waste recycling. By the end of 2016, about 1529 waste recycling companies were registered, among which 80% are private companies. The total recycling quantity of recyclable wastes reached 7.11 Mt in 2016. Table 1 lists the detailed recycling components. The key challenge is that it is difficult to recycle many low value wastes, such as package waste plastic & paper, plate glass, waste fiber, discarded clothes and furniture. These wastes have to be delivered to local landfills for final disposal.

3. Methods and data sources

Recycling wastes can achieve lifecycle benefit, because it can not only reduce total wastes to the landfills, but also can preserve natural resources and reduce corresponding production process pollution (Colling et al., 2016; Ho et al., 2017; Tan et al., 2015). Therefore, the energy saving and CO_2 reduction effect in this paper are evaluated from a lifecycle perspective. Considering that not enough such studies have been conducted and there are no mature methods, embodied energy/carbon method as a feasible method is proposed to evaluate the lifecycle environmental effect of recyclable waste recycling. As for emerging RPF technology, the embodied energy/carbon coefficient is still not available. Therefore, existing company production data are referred to get the lifecycle data of RPF. The detail calculation of energy saving and CO_2 reduction effect for recyclable waste and RPF are introduced in section 3.1 and 3.2, respectively.

3.1. Energy saving and carbon emission reduction of recyclable wastes

Embodied energy is defined as the sum of all the energy consumed during the life cycle of products and services, including energy consumption of material extraction, processing and transportation to the final utilization (Ding, 2004; Foraboschi et al., 2014). It is useful in determining the effectiveness of energy-saving devices or products. Similar to the concept of embodied energy, embodied carbon can address the concerns of lifecycle CO_2 emissions and is useful in deciding whether a product contributes to or mitigates global warming. Embodied energy (and carbon) has particularly been widely used in the context of buildings (Karimpour et al., 2014; Lamnatou et al., 2014) and construction materials (Cabeza et al., 2013b; Su and Zhang, 2016). In addition, several studies investigated the potential to use recyclable materials/components to reduce the embodied energy and carbon (Cabeza et al., 2013a; Thormark, 2002).

Equations (1)–(3) show how to calculate energy saving and carbon emission reduction (ΔE) of recyclable wastes recycling by using embodied energy/carbon method.

$$E_{raw} = M_{raw} \times f_{raw} \quad (1)$$

$$E_{recy.} = M_{recy.} \times f_{recy.} \quad (2)$$

$$\Delta E = E_{raw} - E_{recy.} \quad (3)$$

Where, E_{raw} and $E_{recy.}$ represent the embodied energy (or embodied carbon) of raw materials and recycled wastes, respectively. M is the quantity of materials. f_{raw} *and* $f_{recy.}$ represent the embodied energy (or embodied carbon) coefficients to produce one unit of raw materials and recycled materials, respectively. The key for this method is to get two types of data, namely, the quantity data (M) and the coefficients (f) for different virgin or recycled materials. The quantity data can be obtained from survey or statistical data, while the coefficients data are obtained from *Inventory of Carbon and Energy* (ICE) database initiated by University of Bath in UK.

The ICE database is an open-access and reliable database for embodied energy and carbon associated coefficients, covering more than 200 different types of construction material (Hammond and Jones, 2008). The default boundary of the embodied coefficient in this ICE database is “cradle-to-gate” that includes total energy (carbon) until the products leaves the factory gate, that is to say, the end of life stage is not considered (Hammond and Jones, 2008). The embodied coefficients used in this paper were selected from the ICE database version 1.6a (Geoff and Craig, 2008). Table 2 lists the detailed values of these coefficients.

3.2. Energy saving and carbon emission reduction of RPF

Besides the recyclable wastes, a large quantity of non-recyclable wastes still exists and need to be better managed. For instance, a lot of waste paper and plastics mixed in the MSW are sent to the landfills. However, such wastes can be reutilized through the application of RPF technology so that they can be transferred to a kind of solid fuel pellets (Li et al., 2009). RPF can be used as a substitute of fossil fuels in industrial sectors, such as dying, iron & steel, chemical, *etc*. The heat value of RPF is almost the same as coal, while its carbon emission coefficient is much lower, about 40% of CO_2 from coal (Earthtechnica Co. Ltd. and Sekishouten Co. Ltd., 2014). Moreover, RPF has many advantages such as easy operation, flexible in pellets size control, possible to adjust heat value,

Table 1
Main recyclable wastes recycling in Shanghai during 2014–2016 (thousand tonnes).

Year	Waste steel	Waste nonferrous metal	Waste paper	Waste plastic	Waste rubber	Waste glass	WEEE	End-of-life vehicles (No.)
2014	4298.7	428.3	946.5	153.0	13.9	593.4	136.5	/
2015	4108.6	556.6	962.8	246.4	27.4	450.0	220.0	40,713
2016	4114.1	545.0	951.1	217.3	19.1	652.3	51.1	42,032

Source: (SRRTA, 2015, 2016).

Table 2
Embodied coefficients for raw materials and recyclable wastes [ICE, 2008].

Materials	Raw materials		Recyclable wastes	
	Embodied energy (MJ/kg)	Embodied carbon ($kgCO_2$/kg)	Embodied energy (MJ/kg)	Embodied carbon ($kgCO_2$/kg)
Ferrous metal	35.3	2.75	9.5	0.43
Non-ferrous metal (Al)	224.1	11.78	17.9	0.94
Paper cardboard	35.5	1.89	25.66	1.36
Waste plastic	109.5	2.28	21.9	0.46
Glass bottles	17.98	1.02	6.63	0.38
Rubber	101.7	3.18		
Wood	37.42	2.03	3.43	0.19

economic thrifty and stable quality. Therefore, it has been widely used, particularly in Japan, as a useful method of saving natural resources, reducing landfill volume and reducing greenhouse gas emissions.

Energy saving (E_{RPF}) effects of RPF technology can be calculated by equation (4).

$$E_{RPF} = M_{RPF} \times f_{RPF} = M_{waste} \times 0.67 \quad (4)$$

Where, M_{RPF} is the quantity of RPF production, and M_{waste} is the total quantity of non-reclaimable waste paper, plastic and wood scripts used for RPF production. According to (Chen et al., 2011), one tonne of waste plastic and paper can be produced into 0.67 tonnes of RPF, namely, M_{RPF} equals to 0.67 M_{waste}. Because the calorific values of RPF and coal are the same, it is assumed that one unit of RPF can save one unit of standard coal, namely, energy saving coefficient of RPF (f_{RPF}) is 1.

Carbon emission reduction (C_{RPF}) effects of RPF technology can be calculated by equation (5).

$$C_{RPF} = M_{RPF} \times 2.062 \quad (5)$$

Where, 2.062 is the lifecycle CO_2 emission reduction coefficient of RPF compared with coal (Fig. 2). It is obtained from reference (Earthtechnica Co. Ltd. and Sekishouten Co. Ltd., 2014).

3.3. Data sources

Data used in this study include quantity and components of Shanghai's MSW for the years of 2002–2016, recycling quantity and recycling rates of recyclable solid wastes from 2014 to 2016. The MSW data were obtained from Shanghai Statistical Yearbooks (Shanghai Municipal Statistics Bureau, 2017). The recycling quantity of various wastes were from *Analysis Report on Recyclable Waste Recycling in Shanghai* published by the Shanghai Resource Recycling Trade Association (SRRTA) (SRRTA, 2015, 2016). Data of the MSW components are only available for years 2002–2003 (Zhou et al., 2014), 2007 (Lu, 2012) and 2013 (Dai, 2016). In order to perform reliable analysis, it is assumed that such components for years of 2004–2011 have the same values as those for 2007. Similarly, such components for years 2012–2016 are assumed to have the same values as those for 2013. The recycling rates in Shanghai are not available. Thus, the national average recycling rates (Table 3) are used.

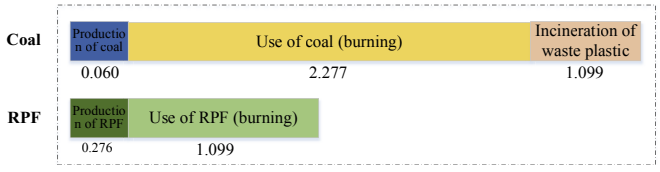

Fig. 2. Life cycle CO_2 emission reduction effect of RPF.

4. Results

4.1. Energy saving and CO_2 reduction effect

Energy saving effect through recycling wastes is about 7.8 million tonnes of standard coal (Mtce), 8.8 Mtce and 8.7 Mtce in years 2014, 2015 and 2016, respectively (Fig. 3). Waste steel and waste nonferrous metal are the major contributors to the total energy saving, with average values of 44% and 42% during 2013–2014, respectively. Waste nonferrous metal has very high embodied energy, which is the main reason for its high energy saving effect. While for ferrous metal, the high recyclable quantity is the main reason for its high contribution in energy saving.

CO_2 reduction effect of recycling wastes in Shanghai is illustrated in Fig. 4, in which the total CO_2 reduction effect of recycling wastes is 15.80 Mt, 16.87 Mt and 16.81 Mt for years 2014, 2015 and 2016, respectively. Recycling waste steel and waste nonferrous metal can significantly reduce CO_2 emission. Waste steel recycling can contribute to CO_2 reduction by about 10 Mt/year from 2014 to 2016, accounting for about 60% of the total CO_2 reduction. Second to waste steel, waste nonferrous metal recycling contributed to about 5.5 Mt/year from 2014 to 2016, accounting for about 33% of the total CO_2 reduction on average. Another finding is that energy saving effect from waste nonferrous metal recycling is relatively higher than its CO_2 reduction effect.

4.2. Energy saving and CO_2 reduction potential of recycling efforts

4.2.1. Scenario 1 (S1): improving recycling rate

China's waste recycling system is still immature and its overall recycling rate is very low (Table 3). Therefore, it is critical for China to increase its recycling rate. Fig. 5 demonstrates energy saving and CO_2 reduction potentials assuming that all the recyclable wastes can be recycled, namely with a 100% recycling rate. Under such an assumption, 6.44 Mt standard coal will be saved and 10.02 Mt CO_2 will be reduced. Waste glass, waste plastic and waste paper are the keys to contribute to energy saving potential, accounting for about 26%, 24% and 20%, respectively. Waste steel and waste nonferrous metal also contribute to about 19% and 10%, respectively. The main reason for high energy saving potential of waste glass, waste plastic and waste paper are due to their huge potential recycling quantity, while the relatively higher energy saving potential of waste steel and waste nonferrous metal are due to their high energy saving intensities. As for the CO_2 reduction potentials, waste steel, waste glass and waste paper are the top three contributors, with values of about 32%, 28% and 20%, respectively. The CO_2 reduction potential of waste steel is much higher while the CO_2 reduction potential of waste plastic is much lower compared with its energy saving potential. This is mainly due to the significant CO_2 emission intensity of waste steel and relatively low CO_2 emission intensity of waste plastic.

Table 3
Recycling rates of recyclable wastes in China.

	Waste steel [a]	waste nonferrous metal [a]	Waste paper [a]	Waste plastic [a]	Waste rubber [a]	Waste glass [b]
Recycling rate	75%	85%	20%	25%	47%	13%

[a] These recycling rates are from the website http://www.spider.com.cn/article-277876.html.
[b] Recycling rate of glass is from the website http://www.100ppi.com/news/detail-20160302-763174.html.

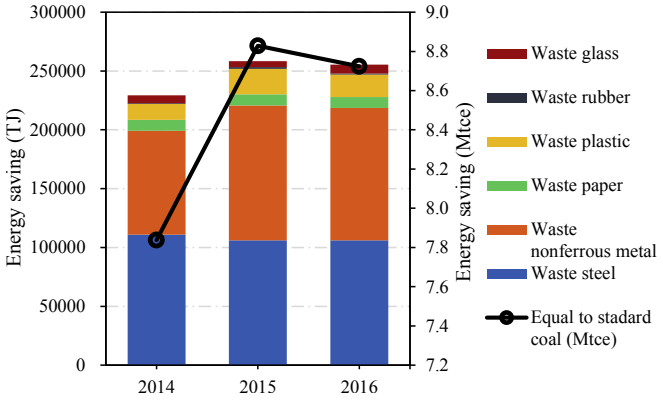

Fig. 3. Energy saving effect of recycling wastes in Shanghai.

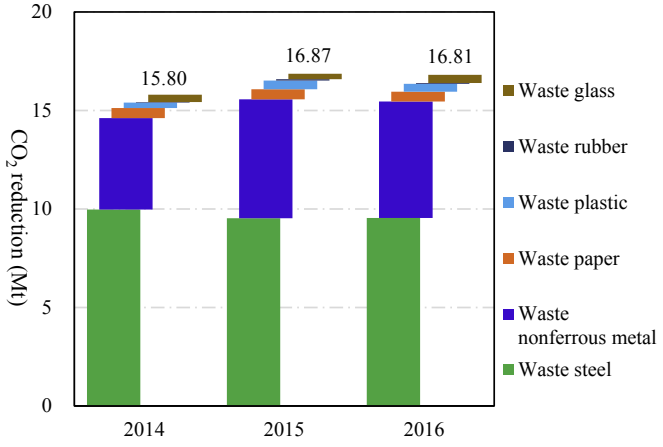

Fig. 4. CO_2 reduction effect of recyclable wastes recycling in Shanghai.

4.2.2. Scenario 2 (S2): further application of RPF technology

The environmental effects are shown in Fig. 6. It is clear that the total energy saving effect increased from about 0.55 Mtce in 2002 to 0.93 Mtce in 2015. The total CO_2 reduction effect is about 2.76 Mt CO_2 in year 2016, with about 53% of direct reduction from fuel burning stage and 47% of indirect reduction from fuel production and waste treatment stage. The energy saving potentials of non-reclaimable waste plastic and paper through RPF technology (S2) (1.24 Mtce) is only half of that of the recyclable waste plastic and paper in S1 (2.83 Mtce), while the CO_2 reduction potential of non-reclaimable waste plastic and paper (S2) (2.76 Mt CO_2) is almost similar to that of the recyclable waste plastic and paper in S1 (2.96 Mt CO_2).

4.2.3. Total energy saving and CO_2 reduction potential

Table 4 lists the current situations of recycling wastes and the potentials in energy saving and CO_2 reduction. The total energy saving and CO_2 reduction for existing system during 2014–2016 are 7.8–8.8 Mtce and 15.8–16.8 Mt CO_2, respectively. The environmental benefits are relatively stable and do not vary too much. As to the potentials for further reducing energy consumption and CO_2 emission, they are about 6.7–7.7 Mtce and 11.7–12.8 Mt CO_2, respectively. This demonstrates that about 85–88% of energy saving and 74–76% of CO_2 reduction potential can be further explored from Shanghai's waste recycling through intensify recycling system and promoting RPF technology. It is also found that the reduction potential of scenario 1 is much higher than scenario 2, indicating that the improvement of recycling rate is more effective than the application of RPF technology. The main reason is that scenario 1 includes reductions from many wastes such as waste steel, waste glass, waste plastic, waste paper and waste rubber, while RPF focuses only on waste plastic and waste paper.

5. Discussions

Calculation of waste recycling process for Shanghai can be illustrated in Fig. 7. Environmental benefit of current recycling was first estimated to identify existing environmental benefit and

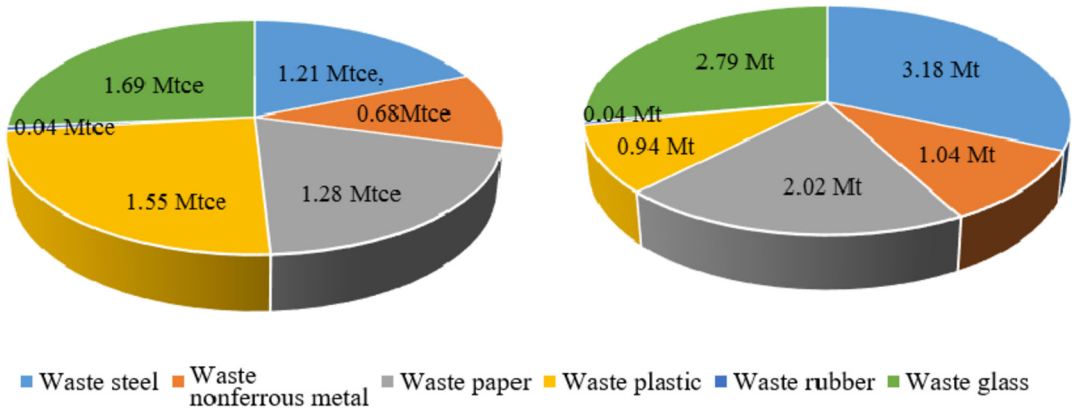

Fig. 5. Energy saving (left) and CO_2 reduction potentials (right) by improving recycling rates.

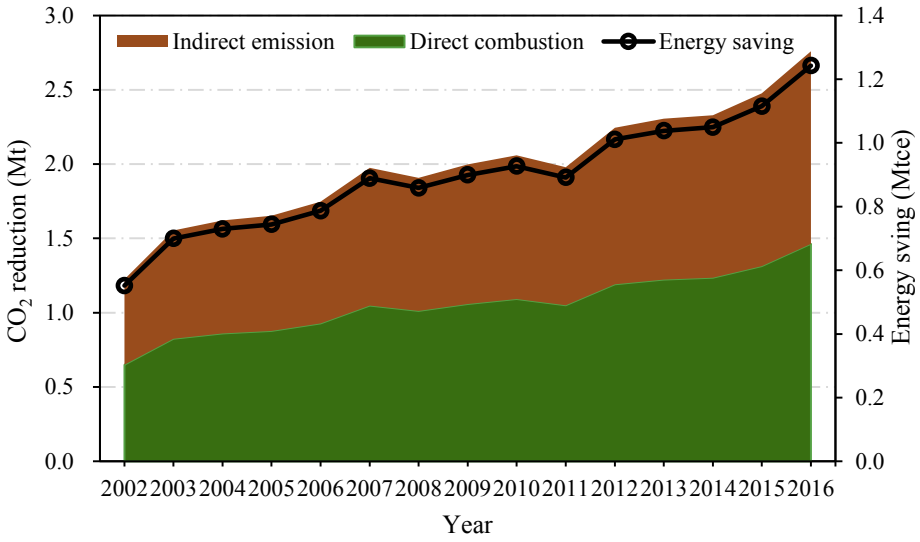

Fig. 6. Energy saving and CO_2 reduction potentials by adopting RPF technology.

Table 4
Energy saving and CO_2 reduction potentials.

		Current	Reduction potential		
			S1	S2	Total
Energy saving (Mtce)	2014	7.84	5.73	1.05	6.77
	2015	8.83	6.17	1.12	7.29
	2016	8.72	6.44	1.24	7.69
CO_2 reduction (Mt)	2014	15.80	9.39	2.33	11.72
	2015	16.87	9.34	2.48	11.82
	2016	16.81	10.02	2.76	12.78

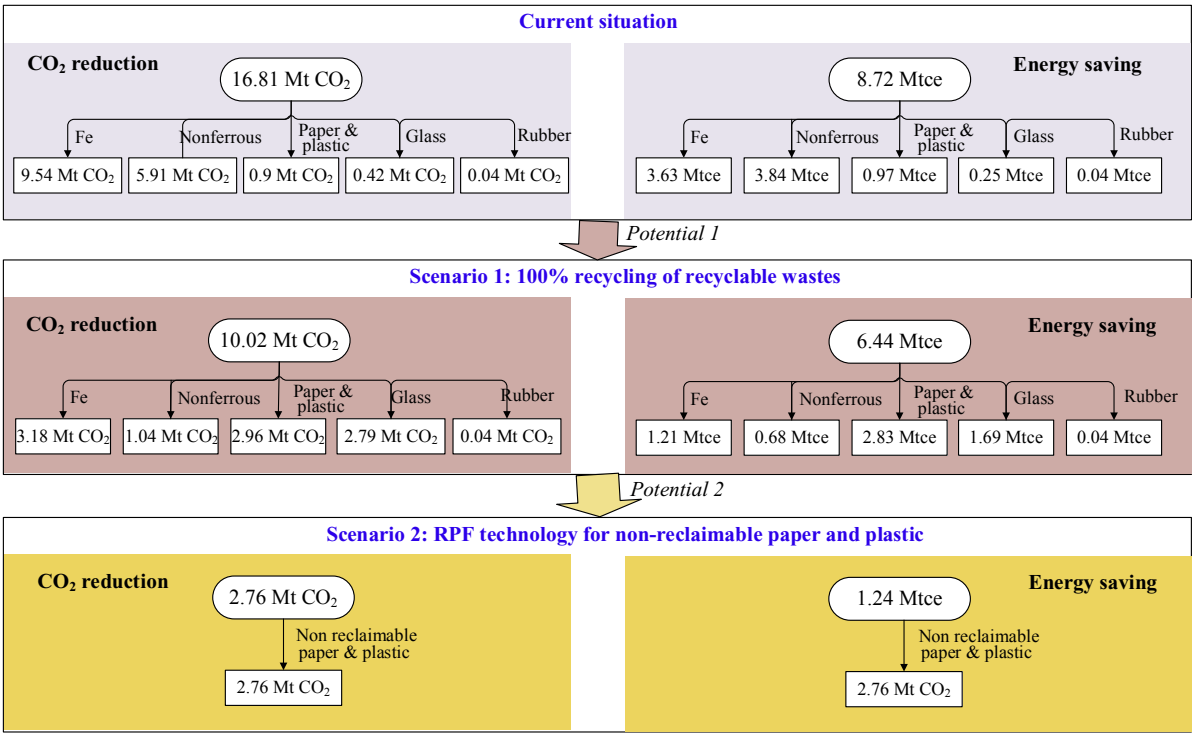

Fig. 7. Flow chart for Shanghai's waste recycling process (the values are year 2016).

potential CO_2 reduction and energy saving quantity. Taking 2016 for example, the energy saving and CO_2 reduction of existing recycling system reached to 1 tce/t MSW and 1.9 t CO_2/t MSW, respectively. Compared to the results of Nigeria cities, which are only 0.0001 tce/t MSW of energy saving and 0.18 Mt CO_{2eq}/t MSW of GHG reduction because of their even lower recycling rate (Ayodele et al., 2018), the environmental effect from urban waste recycling for Shanghai is much better. This indicates that more potential recycling benefits may be achieved for less developed Chinese cities. Then two scenarios from perspectives of increasing existing recycling rate for recyclable wastes (scenario 1) and adopting RPF technology for recycling of non-reclaimable wastes (Scenario 2) were proposed. The total potentials for CO_2 reduction and energy saving in 2016 were 12.78 Mt CO_2 and 7.69 Mtce, respectively.

The contribution of recycling wastes to the total energy consumption and CO_2 emission in Shanghai was further investigated so that the importance of recycling activities can be recognized. The total energy consumption of Shanghai was 114 Mtce in 2016, equal to 254 Mt CO_2 (Table 5). The existing recycling activities could help to reduce about 7–8% of Shanghai's total energy consumption and 6–7% of CO_2 emission reduction. After implementing recycling measures, 6.6% more energy and 4.9% more CO_2 reduction could be achieved for Shanghai. Such a value is not very significant compared to the effect caused by technology upgrade under command-control policies or carbon tax policies (Dong et al., 2017; Ru et al., 2010). Nevertheless, it still contributes to better MSW management and resource conservation. Moreover, the production process cost of recycling wastes is usually lower than that of the traditional raw material production. Therefore, it is relatively easier to be accepted by government and companies. Moreover, recycling businesses can create more job opportunities to the local citizens, a great social benefit to the local communities. Consequently, it would be appropriate to further promote such activities in Shanghai by preparing suitable policies.

First, it is highly suggested that the recycling wastes should be strengthened and improved as soon as possible through the establishment of a mature recycling system. The main barrier for increasing recycling rates in China is a lack of a mature recycling system. Such a system relies on accurate and timely data and information so that recyclable wastes can be easily found and collected. Most companies operate their businesses by their own and do not share byproducts information. Also, comparing with developed countries, the general public do not have adequate environmental awareness, further impeding the recycling activities. In addition, a mature recycling system requires the establishment of relevant infrastructure, a big challenge to many developing cities (Zhang et al., 2016). Consequently, the Shanghai government should pay more attention on establishing such a recycling system by considering its own reality. Fortunately, as the richest Chinese city, Shanghai has sufficient funds to construct necessary infrastructure, such as wastes collection vehicle fleets, wastes storage and separation sites, and waste recycling facilities. In addition, the local government can actively encourage all the stakeholders to engage in establishing this recycling system so that all the stakeholders can share their wastes generation data and information, especially the spatial distribution of such recyclable wastes so that more recycling opportunities can be recognized and more recycling firms are eager to involve in. Moreover, the local government should initiate more capacity-building activities to improve local public's environmental awareness and change their behaviors, such as TV and radio promotions, regular workshops, outdoor billboards, and Internet promotions.

Second, RPF technology can be a promising MSW treatment method that should be promoted in Shanghai to respond the increasing quantity of non-reclaimable waste plastic and paper. Most existing recycled waste plastic and waste paper are from industrial production or high value plastics such as PET bottles or high value paper such as paperboard, newspaper, printing paper mixed in MSW. However, due to rapid development of express delivery in China, large quantities of packaging wastes are generated. Most of them are discarded directly to the trash bins and finally sent to the landfills or incineration factories (Song et al., 2018), leading to the loss of further recycling. In fact, CO_2 reduction effect from recycling packaging materials is much higher than the option of waste-to-energy or composting (Giugliano et al., 2011). Therefore, the Shanghai government should consider further applying RPF technology so that these non-reclaimable waste plastic & paper and packaging waste mixed in MSW can be used for making RPF.

6. Conclusions

China's rapid development induces an urgent need to reduce the overall solid wastes. Although more landfills have been built up and more will be constructed in the near future, recycling wastes is one effective method due to its clear carbon emission reduction and other environmental emissions reduction effects. However, challenges exist and impede the application of wastes recycling. Under such a circumstance, this paper investigates energy saving and CO_2 reduction effect of recycling wastes by taking the largest Chinese megacity Shanghai as a case study. Also, the potential energy saving and CO_2 reduction by increasing waste recycling rates and adopting RPF technology are further investigated.

Three main findings are obtained. First, energy saving and CO_2 reduction effect of Shanghai's waste recycling system were 8.7 Mtce and 16.81 Mt CO_2 in 2016, respectively. Waste steel recycling and nonferrous metal recycling were the two dominant contributing factors, adding up to accounting for about 86% of energy saving and

Table 5
Energy saving and CO_2 reduction ratios compared to total emissions in Shanghai.

		Shanghai totals	Existing recycling		Recycling potentials	
			Quantity	Ratio	Quantity	Ratio
Energy saving (Mtce)[a]	2014	110.85	7.84	7.07%	6.77	6.11%
	2015	113.87	8.83	7.75%	7.29	6.40%
	2016	117.12	8.72	7.45%	7.69	6.56%
CO_2 reduction (Mt)[b]	2014	246.85	15.80	6.40%	11.72	4.75%
	2015	253.60	16.87	6.65%	11.82	4.66%
	2016	260.83	16.81	6.44%	12.78	4.90%

Note:
[a] For Shanghai total, it means the total energy consumption but not energy saving. It was obtained from Shanghai Statistical Yearbook 2017 (Shanghai Municipal Statistics Bureau, 2017).
[b] For Shanghai total, it means the total CO_2 emission but not CO_2 reduction. It was calculated by equation: total energy consumption $\times$2.227 tCO_2/tce.

93% of CO_2 reduction. Second, recycling of waste steel and nonferrous metal showed similar energy saving contribution, about 44% and 42%, respectively. However, the CO_2 reduction effect from waste steel recycling was much higher than that of nonferrous metal, with values of 60% and 33%, respectively. The main reason was due to the large CO_2 reduction coefficient of waste steel recycling compared with waste nonferrous metal recycling. Third, energy saving and CO_2 reduction potential were estimated to be 7.69 Mtce and 12.78 Mt CO_2 in 2016, respectively, with about 80–85% from increasing recycling rates and 10–15% from applying RPF technology. Moreover, the potential is mainly from further recycling of waste glass, waste plastic & paper, and waste steel, contributing to about 49%, 22% and 15% of energy saving and 45%, 22% and 25% of CO_2 reduction, respectively. In order to improve the overall recycling level, policy suggestions on how to promote the establishment of mature recycling system and advocate PRF technology are raised to decision makers so that they can prepare more appropriate policies on establishing a better waste recycling system and promoting the application of PRF technology.

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